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Cassini-Huygens Maneuver Experience: Second Year of Saturn Tour

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This paper documents the maneuver experience during the second year of the Cassini-Huygens mission at Saturn. Since Saturn arrival in July 2004, the Cassini orbiter has made many flybys of Titan and Saturn's icy satellites. From August 2005 to June 2006, there were 39 planned maneuvers designed to target Cassini to aimpoints near Titan, Hyperion, Dione, and Rhea. Highlights of this paper include maneuver designs and strategies, maneuver performance, maneuver cancellation rationales, and a new maneuver execution-error model based on maneuvers executed to date.

I. Introduction

The Cassini-Huygens spacecraft was successfully inserted into an orbit around Saturn on 01-Jul-2004, beginning a planned four-year tour of the Saturnian system. The first year of the Saturn tour saw the accurate targeting of the Cassini orbiter to six close flybys of Saturn's largest moon, Titan, and to two close encounters of the icy satellite Enceladus. The crowning achievement was Cassini's precise delivery of the European Space Agency's (ESA) Huygens probe to the surface of Titan on 14-Jan-2005, the farthest landing ever made from Earth and the first successful landing on a moon of another planet. The second year of the Saturn tour also contained significant milestones in navigation. From August 2005 to July 2006, Cassini achieved the first targeted close encounters of the icy satellites Hyperion, Dione, and Rhea, and made 10 more targeted close flybys of Titan. This paper documents the navigational experience, from a maneuver analyst's perspective, throughout the second year of exploration of the Saturnian system. Earlier papers from the Navigation team reported on maneuvers planned during early interplanetary cruise,[1] inner cruise,[2] end of cruise and arrival at Saturn,[3] and the first year of Saturn tour[4] (covering maneuvers scheduled from 03-Jul-2004 to 08-Jul-2005).

From 03-Aug-2005 to 28-Jun-2006, there were 39 planned Orbit Trim Maneuvers (OTMs). These maneuvers, OTM-026 through OTM-064, were designed to target the Cassini orbiter to aimpoints near Titan, Hyperion, Dione, and Rhea. Two Titan encounters in August and September 2005 reduced the orbit inclination to near Saturn's equator to setup the icy satellite encounters. From September 2005 to June 2006, maneuvers were performed to produce a series of alternating outbound/period-reducing and inbound/period-increasing Titan flybys to rotate Cassini's orbit clockwise around Saturn toward the magnetotail, placing apocrone (Saturn-relative apoapsis) near the anti-Sun direction. Of the planned 39 maneuvers, over one-third were cancelled. Reasons for maneuver cancellations included the following: accurate delivery to an encounter was not required, accurate delivery to an encounter was already achieved with a prior maneuver, and/or maneuver was too small to be performed or implemented.

This paper gives a detailed account of the 39 maneuvers scheduled during the second year of the Saturn tour. Specifically, this paper discusses the maneuver strategies that were employed, the maneuver cancellation process that was developed to deal with the increased frequency of maneuvers that are candidates for cancellation, and the execution error models developed and implemented.

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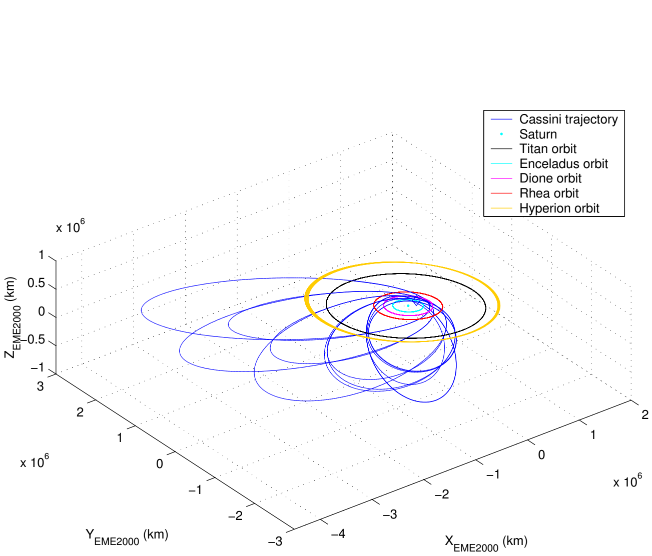
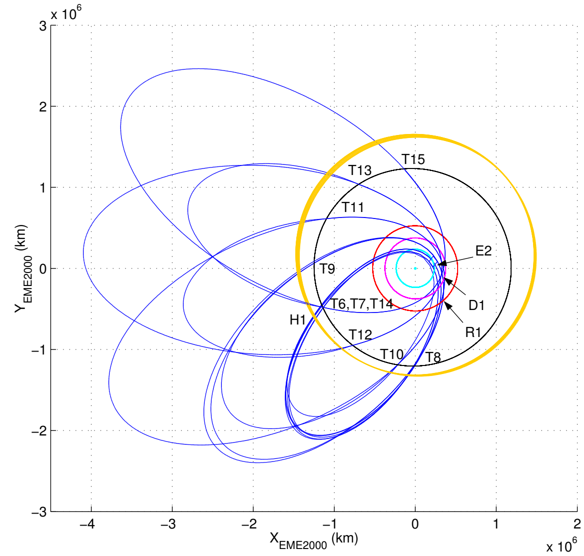
II. Saturn Tour Description

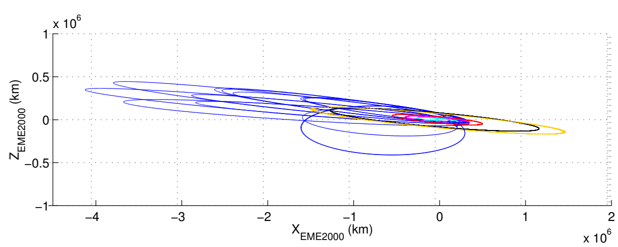
Figure 1 illustrates the planned trajectory from the Titan-6 (T6) encounter on 22-Aug-2005 to the Titan-15 (T15) encounter on 02-Jul-2006. There was a total of 10 targeted Titan flybys, one Hyperion flyby, one Dione flyby, and one Rhea flyby during this time period. These encounters are labeled with a one/two letter and number designation (e.g., H1 for Hyperion-1). It can be seen in figures 1c and 1d that the trajectory during this portion of the Saturn tour was mainly in the Saturn equatorial plane (i.e., zero inclination).



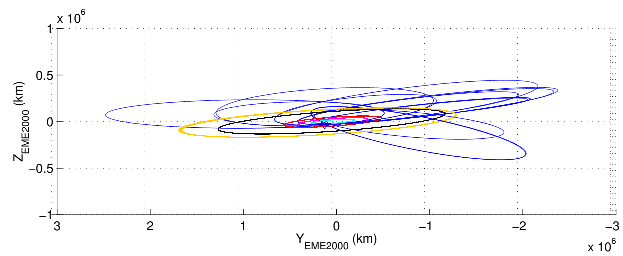
(a) X-Y-Z Space



(b) X-Y Plane



(c) X-Z Plane



(d) Y-Z Plane

Figure 1. Cassini Tour Trajectory Segment: Titan-6 (T6) to Titan-15 (T15), August 2005 - July 2006. *Saturn Centered Earth Mean Equator and Equinox of J2000.0 (EME2000) coordinates.*

Table 1 lists the targeted encounter conditions and the achieved flyby differences for each encounter from T6 to T15. The $\mathbf{B} \cdot \mathbf{R}$, $\mathbf{B} \cdot \mathbf{T}$, and time of closest approach (TCA) target conditions, expressed in EMO2000 coordinates, were defined in the reference trajectory and used in the final maneuver designs. The flyby differences from the reference trajectory, which were the differences between the actual flybys and the designed, reveal that most encounters were within 10 km and a few seconds from planned conditions, even when one or more maneuvers were cancelled, as seen later in table 5. The accuracy of the flybys from T6 to T10 are explored in detail in Ref. 5. The hyperbolic excess velocity at the incoming asymptote of an encounter (V_∞), is also provided in the table for each flyby.

The reference trajectory history since the beginning of the Saturn tour is presented in table 2. The reference trajectory defines the flyby target conditions ($\mathbf{B} \cdot \mathbf{R}$, $\mathbf{B} \cdot \mathbf{T}$, TCA) and the (approximate) locations of the deterministic maneuvers (cleanup and apocrone maneuvers). (See Ref. 3 for the reference trajectory history from April 2000 to June 2004.) The 050720 reference trajectory was used from 15-Jul-2005 to 22-Mar-2006 for the maneuver designs of OTM-026 to OTM-056 and the encounter conditions of T6 through T12. After the OTM-056 final design on 22-Mar-2006, the 060323 reference trajectory was implemented for the maneuver designs of OTM-057 through OTM-064 and the encounter conditions of T13 through T15.

Table 1. Targeted Encounter History (T6 to T15)

Encounter			Reference Trajectory Target Conditions (Earth Mean Orbital Plane and Equinox of J2000.0)				Flyby Differences from Reference Trajectory[‡]		
I = Inbound, O = Outbound		V_∞ ($\frac{km}{s}$)	B·R (km)	B·T (km)	Time of Closest Approach (ET/SCET)[*]	Alt.[†] (km)	B·R (km)	B·T (km)	TCA (s)
Titan-6 (T6)[‡]	O	5.61	3493.62	-5507.97	22-Aug-2005 08:54:41	3669	4.43	12.84	0.89
Titan-7 (T7)	O	5.65	3907.82	-328.74	07-Sep-2005 08:13:02	1075	-0.15	-4e-03	-0.02
Hyperion-1 (H1)[‡]	O	5.64	300.47	-565.10	26-Sep-2005 02:25:50	510	1.11	26.23	2.92
Dione-1 (D1)[‡]	I	9.10	607.78	-869.53	11-Oct-2005 17:53:06	500	6.07	5.58	-1.47
Titan-8 (T8)[‡]	I	5.54	-1368.20	-3981.87	28-Oct-2005 04:16:29	1353	-0.60	0.07	-0.43
Rhea-1 (R1)	I	7.29	685.91	1065.16	26-Nov-2005 22:38:43	500	-2.91	4.34	-0.41
Titan-9 (T9)[‡,§]	O	5.49	-6012.93	-11838.63	26-Dec-2005 19:00:34	10409	-12.85	4.00	-3.94
Titan-10 (T10)[‡]	I	5.48	-991.65	-4806.87	15-Jan-2006 11:42:31	2043	1.16	0.10	-0.10
Titan-11 (T11)[‡]	O	5.51	-1841.04	-4297.24	27-Feb-2006 08:26:23	1813	1.31	0.68	0.60
Titan-12 (T12)[‡]	I	5.47	220.65	-4811.44	19-Mar-2006 00:07:01	1951	0.29	1.67	-0.39
Titan-13 (T13)	O	5.49	-1102.90	-4587.76	30-Apr-2006 20:59:19	1855	-1.81	-0.79	-0.14
Titan-14 (T14)	I	5.48	1280.80	-4567.23	20-May-2006 12:19:16	1879	0.02	-0.40	0.10
Titan-15 (T15)	O	5.48	70.12	-4769.87	02-Jul-2006 09:21:52	1906			

[*] Ephemeris time (ET) / spacecraft event time (SCET).
[†] Altitude not explicitly targeted in maneuver designs.
[‡] Flyby differences from reference trajectory target conditions may appear large due to cancelled maneuver(s).
[§] Reference trajectory target conditions not implemented.

Table 2. Reference Trajectory History (Since September 2004)

Name	Released	Comments
041001	30-Sep-2004	Increased the distance the probe passes by a non-targeted Iapetus encounter on rev C.[6]
041210	09-Dec-2004	Raised T5 and T7 flyby altitudes.[6]
050505	02-May-2005	Implemented 1500 km Rev-15 Tethys non-targeted flyby, lowered H1 and E2 periapses, and moved OTM-038.[7]
050720	15-Jul-2005	Raised T7 altitude from 1025 km to 1075 km.
060323	13-Mar-2006	Raised minimum altitude of Titan flybys.

III. Maneuver Execution

The Cassini tour of Saturn was designed to take advantage of the substantial gravity assists provided by each Titan flyby, with closer flybys imparting larger ΔVs to the spacecraft. For instance, a Titan flyby at an altitude of 950 km and a V_∞ of 6 km/s supplies an equivalent ΔV of about 800 m/s to Cassini. During tour, propulsive maneuvers are necessary not only to correct the spacecraft's trajectory due to flyby dispersions, but also to change the trajectory when Titan gravity assists are not sufficient. Maneuvers are accomplished through the use of two independent propulsion systems. The bi-propellant main engine (ME) assembly (with two main engines MEA and MEB) performs large maneuvers, while the Reaction Control System (RCS) thrusters handle small trajectory corrections.[8] A "cut-off" criterion for the main engine of 0.3 m/s has been adopted for choosing either ME or RCS for a maneuver (i.e., a maneuver greater than 0.3 m/s would generally be performed on ME). Main engine MEA has been used for every ME burn since launch. The coordinate system for the spacecraft is labeled in figure 2: $X_{S/C}$, $Y_{S/C}$, and $Z_{S/C}$. The $Z_{S/C}$ axis points from the high gain antenna to the ME, the $X_{S/C}$ axis points away from where Huygens was attached, and the $Y_{S/C}$ axis completes the right-handed system.

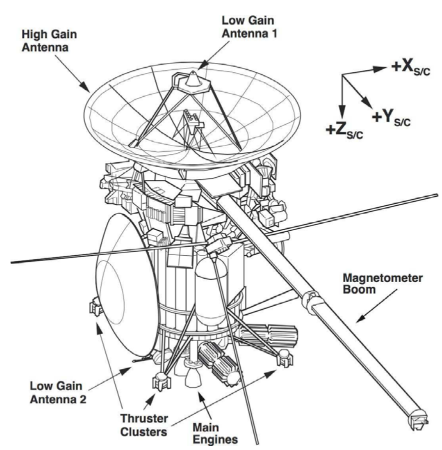


Figure 2. Cassini-Huygens Spacecraft

Several ΔVs associated with a maneuver contribute to the total ΔV imparted to the spacecraft. These include, but are not limited to, deadband tightening and limit cycling, roll and yaw turns, pointing-bias-fix turns,[2] the burn itself, and Reaction Wheel Assembly (RWA) rotation rate changes (or biases). Generally, only the burn and turn ΔVs are considered in the total ΔV, with other ΔV events added when analyzing execution errors (except for RCS burns, where deadband tightening and limit cycling are also considered in the total ΔV).

Maneuver execution errors represented using the Gates model[9] account for four independent error sources, fixed- and proportional- magnitude errors and fixed- and proportional- pointing errors. The direction of pointing errors is assumed to have a uniform distribution across 360°. Assuming a Gaussian distribution, each parameter represents the standard deviation for that error source and each error source is assumed to have a zero mean. Table 3 shows the 2000 execution-error model[10] used for ME and RCS burns from April 2000 to February 2006. The 2006-01 execution-error model,[11,12] given in table 4, has been in use since March 2006 for ME and RCS starting with the OTM-053 maneuver design.

Table 3. 2000 Maneuver Execution-Error Model[10] (1-σ)

		ME	RCS
Magnitude	Proportional (%)	0.2	2.0
	Fixed (mm/s)	10.0	3.5
Pointing	Proportional (mrad)	3.5	12.0
(per axis)	Fixed (mm/s)	17.5	3.5

Table 4. 2006-01 Maneuver Execution-Error Model[11] (1-σ)

		ME	RCS
Magnitude	Proportional (%)	0.04	0.7
	Fixed (mm/s)	6.5	0.9
Pointing	Proportional (mrad)	1.0	12.0
(per axis)	Fixed (mm/s)	4.5	3.5

IV. Maneuver Strategies

The navigation strategy since launch has been to target the spacecraft to encounter conditions defined in the reference trajectory. In particular, the navigation strategy during the Saturn tour has been to target to three B-plane parameters of an upcoming encounter; the spatial components $\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$ and the temporal component time-of-flight (TF). For an explanation of the B-plane, see "Appendix: B-Plane Description." Since the Cassini to Huygens probe relay during the Titan-C (Tc) flyby on 14-Jan-2005, the control of the spacecraft trajectory has been accomplished with three propulsive Orbit Trim Maneuvers (OTMs) between each targeted Titan or icy satellite encounter: a flyby cleanup maneuver, an aprocrone (Saturn-relative apoapsis) targeting maneuver, and an approach targeting maneuver. Past studies have shown that any additional maneuvers between encounters do not significantly lower the ΔV requirements.[13] Figure 3 illustrates this maneuver strategy for an outbound-to-inbound[a] Titan transfer. Usually performed three days after an encounter, the cleanup maneuver is used to correct trajectory errors from a previous flyby. The cleanup maneuver location depends on the time required to converge the orbit determination (OD) process after the encounter, and the time required for maneuver designing, sequencing, and uplinking. The first maneuver targeted to an encounter is normally

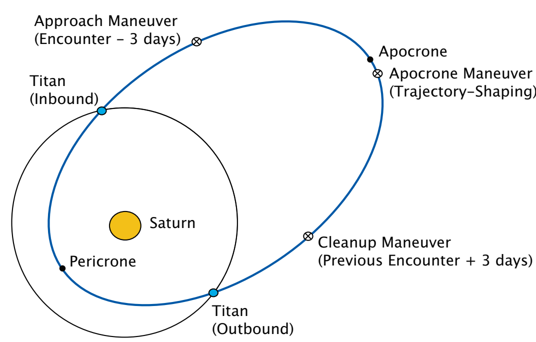


Figure 3. Maneuver Strategy for Saturn Tour

[a]An outbound flyby occurs after pericrone (Saturn-relative periapsis). Conversely, an inbound encounter occurs before pericrone.

performed near apocrone (within a few days) to "shape" the trajectory in order to achieve the flyby conditions. The approach maneuver, the last targeting maneuver and completely statistical, is generally executed three days before an encounter to cleanup errors from the apocrone maneuver and to achieve as accurate flyby conditions as possible. The approach maneuver location avoids interference with science measurements during the encounter period and allows enough time to perform a backup maneuver if necessary.

The targeting maneuvers in each encounter leg (generally the aprocrone and approach maneuvers) are computed by the K-inverse strategy which entails correcting three components of the B-plane miss: $\mathbf{B}\cdot\mathbf{R}$, $\mathbf{B}\cdot\mathbf{T}$, and TF. Specifically, the ΔVs are calculated by the following:

$$\Delta V = -K^{-1}\Delta B \tag{1}$$

where K is a 3×3 matrix of partial derivatives of the B-plane miss parameters with respect to the spacecraft velocity ($K = \frac{\delta\Delta B}{\delta V}$) and ΔB is the B-plane error ($\Delta\mathbf{B}\cdot\mathbf{R}$, $\Delta\mathbf{B}\cdot\mathbf{T}$, and ΔTF).

Flyby cleanup maneuvers are often designed with a chained two-impulse optimization strategy, which minimizes the sum of the first two deterministic maneuvers in a leg (in this case, the cleanup and apocrone maneuvers) across several encounters. The first maneuver in each leg (the cleanup maneuver) is computed by minimizing the following cost function:

$$J_i = \underbrace{||\Delta V_{i\_1}|| + ||\Delta V_{i\_2}||}_{leg\ i} + \underbrace{||\Delta V_{i+1\_1}|| + ||\Delta V_{i+1\_2}||}_{leg\ i+1} + \underbrace{||\Delta V_{i+2\_1}|| + ||\Delta V_{i+2\_2}||}_{leg\ i+2} + ... \tag{2}$$

$$= \sum_{m=0}^{n} ||\Delta V_{i+m\_1}|| + ||\Delta V_{i+m\_2}|| \tag{3}$$

subject to the constraints

$$\Delta(\mathbf{B}\cdot\mathbf{R})_{i+1} = 0,\ \Delta(\mathbf{B}\cdot\mathbf{T})_{i+1} = 0,\ \Delta TF_{i+1} = 0, \tag{4}$$

$$\Delta(\mathbf{B}\cdot\mathbf{R})_{i+2} = 0,\ \Delta(\mathbf{B}\cdot\mathbf{T})_{i+2} = 0,\ \Delta TF_{i+2} = 0,\quad \textit{etc. up to } (i+m) \tag{5}$$

It follows that between N encounters, $2(N-1)$ maneuvers are being optimized ($6(N-1)$ parameters) and $3(N-1)$ constraints are made ($\mathbf{B}\cdot\mathbf{R}$, $\mathbf{B}\cdot\mathbf{T}$, and TF). As an example, the tour usually contains $N = 6$, so that 10 maneuvers are optimized and 15 constraints are made. Besides providing an optimal distribution of the ΔVs over multiple legs, this optimization strategy helps control asymptote errors without actively altering downstream flyby aimpoints after each encounter. Another benefit of this strategy is that the designed cleanup maneuver ΔVs are less sensitive to maneuver time shifts.[14]

V. Maneuver Experience

From 03-Aug-2005 to 28-Jun-2006, there was a total of 39 planned maneuvers, OTM-026 through OTM-064. These maneuvers were designed to target Cassini to aimpoints near Titan, Hyperion, Dione, and Rhea. Of the planned maneuvers during this time frame, over one-third were cancelled, of which three were deleted before the design process began. Table 5 gives the history of these maneuvers in terms of ΔV, separated by encounters (encounter times, flyby altitudes, inbound/outbound). In the table, the location of each maneuver in the orbit is given with the corresponding epoch time. The true anomaly provides a picture of where the spacecraft is in the orbit at the time of the maneuver (e.g., at a value of 180°, the spacecraft is at apocrone). Each ΔV value listed is the sum of the burn and turns ΔVs (and ΔVs due to deadband tightening/limit cycling for RCS burns). The turn ΔVs are the roll and yaw turns associated with orienting the spacecraft for the burn, including the pointing-bias-fix turns for ME burns. The predicted ΔV mean, 1-σ, and 95%[b] values were computed via LAMBIC[c] using the latest reference trajectories (see table 2). These statistical ΔV predictions account for both maneuver and orbit determination (OD) statistical variations. The design ΔVs, computed using SEPV[d], were commanded to the spacecraft. The reconstructed ΔVs were determined by the OD trajectory reconstructions after the maneuvers were performed. Since the reconstructed and predicted ΔVs include maneuver execution errors, the reconstructed ΔVs, as opposed to the design ΔVs, were compared to the predicted ΔVs to determine the prediction errors.

[b]95% ΔV means that the maneuver ΔV size will be less than or equal to this value with a 95% probability.

[c]LAMBIC (Linear Analysis of Maneuvers with Bounds and Inequality Constraints) is a program that simulates the execution of a sequence of maneuvers by computing the statistics of ΔV magnitude and delivery accuracy using the Monte Carlo method (see Ref. 15).

[d]SEPV is a non-linear search path varying program that computes ΔVs that satisfy given sets of encounter conditions.

Table 5. Maneuver History (OTM-026 to OTM-064)

Maneuver	Orbit Location	Maneuver Time (UTC/SCET)[*]	True Anom. (deg)	Predicted ΔV Mean (m/s)	Predicted ΔV 1-σ (m/s)	Predicted ΔV 95% (m/s)	Design ΔV (m/s)	Recon. ΔV (m/s)	Pred. Error[†] (σ)	Burn Type
Enceladus-2 (E2)		14-Jul-2005 19:55:22		Altitude = 175 km			Inbound			
OTM-026	E2+20d	03-Aug-2005 11:50	133.7	2.874	1.262	5.044	2.628	2.622	0.20	ME
OTM-027	~apo	10-Aug-2005 13:21	177.4	2.639	0.211	3.040	2.418	2.416	1.05	ME
OTM-028	T6-4d	18-Aug-2005 11:00	-145.6	0.109	0.076	0.259	- - - - - *CANCELLED* - - - - -			
Titan-6 (T6)		22-Aug-2005 08:53:37		Altitude = 3669 km			Outbound			
OTM-029	T6+3d	25-Aug-2005 17:08	170.3	1.663	1.287	4.199	1.459	1.453	0.16	ME
OTM-030	~apo	30-Aug-2005 18:43	-172.3	14.606	0.201	14.858	14.350	14.357	1.24	ME
OTM-031	T7-4d	03-Sep-2005 17:30	-149.4	0.169	0.100	0.363	0.063	0.065	1.04	RCS
Titan-7 (T7)		07-Sep-2005 08:11:58		Altitude = 1075 km			Outbound			
OTM-032	T7+3d	10-Sep-2005 17:09	167.5	2.580	1.861	6.027	- - - - - *CANCELLED* - - - - -			
OTM-033	H1-6d	19-Sep-2005 16:40	-163.3	27.823	0.646	28.977	27.910	27.930	0.17	ME
OTM-034	H1-3d	23-Sep-2005 07:45	-118.1	0.407	0.228	0.828	- - - - - *CANCELLED* - - - - -			
Hyperion-1 (H1)		26-Sep-2005 02:24:46		Altitude = 510 km			Outbound			
OTM-035	H1+3d	28-Sep-2005 16:11	166.2	1.710	1.252	4.046	0.295	0.296	1.13	RCS
OTM-036	~apo	01-Oct-2005 14:26	176.0	0.166	0.198	0.624	- - - - - *CANCELLED* - - - - -			
OTM-037	D1-3d	08-Oct-2005 09:30	-161.2	0.168	0.118	0.396	- - - - - *CANCELLED* - - - - -			
Dione-1 (D1)		11-Oct-2005 17:52:02		Altitude = 500 km			Inbound			
OTM-038	D1+1d	12-Oct-2005 05:57	73.8	14.874	0.121	15.068	14.829	14.832	0.35	ME
OTM-039	~apo	21-Oct-2005 14:58	-178.2	0.712	0.532	1.736	0.090	0.091	1.17	RCS
OTM-040	T8-3d	25-Oct-2005 07:14	-165.8	0.061	0.030	0.116	- - - - - *CANCELLED* - - - - -			
Titan-8 (T8)		28-Oct-2005 04:15:25		Altitude = 1353 km			Inbound			
OTM-041	T8+3d	31-Oct-2005 13:59	130.4	12.595	0.851	14.156	12.416	12.423	0.20	ME
OTM-042	~apo	13-Nov-2005 14:02	-179.3	2.259	0.784	3.620	2.128	2.126	0.17	ME
OTM-043	R1-3d	23-Nov-2005 13:03	-151.6	0.155	0.098	0.345	0.060	0.060	0.97	RCS
Rhea-1 (R1)		26-Nov-2005 22:37:39		Altitude = 500 km			Inbound			
OTM-044	R1+1d	28-Nov-2005 04:15	103.5	0.526	0.351	1.216	0.237	0.241	0.84	RCS
OTM-045	~apo	11-Dec-2005 11:35	-179.4	0.225	0.146	0.505	- - - - - *CANCELLED* - - - - -			
OTM-046	T9-3d	23-Dec-2005 12:25	-126.0	0.079	0.081	0.205	- - - - - *CANCELLED* - - - - -			
Titan-9 (T9)		26-Dec-2005 18:59:30		Altitude = 10409 km			Outbound			
OTM-047	T9+3d	30-Dec-2005 02:47	161.7	0.260	0.158	0.545	0.183	0.182	0.50	RCS
OTM-048	~apo	03-Jan-2006 02:22	173.9	——	——	——	- - - - - - *DELETED* - - - - - -			
OTM-049	T10-3d	12-Jan-2006 09:23	-160.4	0.240	0.170	0.574	- - - - - *CANCELLED* - - - - -			
Titan-10 (T10)		15-Jan-2006 11:41:26		Altitude = 2043 km			Inbound			
OTM-050	T10+3d	18-Jan-2006 08:37	107.9	0.915	0.695	2.243	- - - - - *CANCELLED* - - - - -			
OTM-051	~apo	02-Feb-2006 07:53	174.9	0.334	0.227	0.773	0.186	0.185	0.65	RCS
OTM-052	T11-3d	24-Feb-2006 06:26	-111.7	0.340	0.328	1.063	- - - - - *CANCELLED* - - - - -			
Titan-11 (T11)		27-Feb-2006 08:25:18		Altitude = 1813 km			Outbound			
OTM-053	T11+3d	02-Mar-2006 05:51	160.4	0.771	0.468	1.675	0.265	0.263	1.09	RCS
OTM-054	~apo	06-Mar-2006 05:36	172.9	——	——	——	- - - - - - *DELETED* - - - - - -			
OTM-055	T12-3d	16-Mar-2006 04:50	-159.7	0.102	0.068	0.240	- - - - - *CANCELLED* - - - - -			
Titan-12 (T12)		19-Mar-2006 00:05:56		Altitude = 1951 km			Inbound			
OTM-056	T12+3d	22-Mar-2006 04:19	116.7	0.667	0.516	1.682	0.467	0.471	0.38	ME
OTM-057	~apo	06-Apr-2006 03:32	175.3	0.314	0.214	0.733	0.370	0.367	0.25	ME
OTM-058	T13-3d	27-Apr-2006 01:59	-127.5	0.075	0.054	0.180	0.075	0.079	0.07	RCS
Titan-13 (T13)		30-Apr-2006 20:58:14		Altitude = 1855 km			Outbound			
OTM-059	T13+3d	04-May-2006 01:28	161.7	0.879	0.578	2.029	0.505	0.510	0.64	ME
OTM-060	~apo	08-May-2006 01:13	173.7	——	——	——	- - - - - - *DELETED* - - - - - -			
OTM-061	T14-3d	18-May-2006 00:41	-158.7	0.385	0.285	0.930	0.118	0.122	0.923	RCS
Titan-14 (T14)		20-May-2006 12:18:11		Altitude = 1879 km			Inbound			
OTM-062	T14+3d	23-May-2006 16:41	116.3	0.437	0.341	1.104	- - - - - *CANCELLED* - - - - -			
OTM-063	~apo	07-Jun-2006 23:24	175.8	1.980	0.283	2.520	1.923	1.916	0.227	ME
OTM-064	T15-3d	28-Jun-2006 22:07	-122.9	0.108	0.076	0.260	0.068			RCS
Titan-15 (T15)		02-Jul-2006 09:20:47		Altitude = 1906 km			Outbound			

[*] Coordinated universal time (UTC) / spacecraft event time (SCET).

[†] Predicted ΔV Error = |Reconstructed ΔV - Predicted ΔV Mean| / Predicted ΔV σ.

The maneuver design characteristics of all maneuvers performed from August 2005 to June 2006 are summarized in table 6. These attributes include the maneuver epoch; the engine type (ME or RCS); the cut-off time for the last radiometric data received by OD; the design total ΔV magnitude, right ascension (RA), and declination (DEC); the roll and yaw turn angles for the spacecraft burn attitude; the Earth-look angle; and the burn duration. The roll and yaw turns are performed before each maneuver (roll-yaw "wind" sequence) to orient the spacecraft for the maneuver burn and after each maneuver (yaw-roll "unwind" sequence) to return to the pre-maneuver spacecraft orientation. The Earth-look angle is the angle between the total ΔV vector and a vector from the spacecraft to Earth (line-of-sight vector). This angle provides insight into the observability of a maneuver because Doppler data, a line-of-sight measurement, allows the Earth-line ΔV component to be immediately and accurately determined. If the look angle is 0°, the magnitude of the maneuver will be well estimated since it is fully observable on the Earth-line. If the look angle is 90°, then only one component of the pointing error will be well estimated. Since the spacecraft is Earth-pointed prior to each maneuver,[e] the magnitude of the Earth-look angle is approximately equal to the yaw turn angle for each maneuver, as seen in table 6. For an ME burn, the magnitudes of these angles are slightly different because the additional ΔV from the yaw turn. Since an RCS burn is on RWA for the yaw turn, there is no difference in the magnitudes of these angles.

Table 6. Maneuver Design Characteristics (August 2005 - June 2006)

	Maneuver Epoch (UTC/SCET)*	Burn Type	OD DCO† (days)	ΔV Mag. (m/s)	ΔV RA (deg)	ΔV DEC (deg)	Roll Turn (deg)	Yaw Turn (deg)	Earth Look (deg)	Burn Time (s)
OTM-026	03-Aug-2005 11:50	ME	-1.9	2.628	37.70	20.52	90.76	-97.76	99.60	16.6
OTM-027	10-Aug-2005 13:21	ME	-1.6	2.418	152.18	-57.58	-146.37	-97.74	99.56	15.4
OTM-029	25-Aug-2005 17:08	ME	-0.8	1.459	74.33	-44.24	164.54	-98.43	100.00	9.3
OTM-030	30-Aug-2005 18:43	ME	-1.8	14.350	166.34	-57.15	-139.85	-95.13	97.26	91.5
OTM-031	03-Sep-2005 17:30	RCS	-0.8	0.063	108.85	11.33	123.71	-159.47	159.47	68.1
OTM-033	19-Sep-2005 16:40	ME	-3.8	27.910	193.06	7.19	78.58	-116.08	118.11	176.2
OTM-035	28-Sep-2005 16:11	RCS	-1.8	0.295	27.85	-6.00	106.74	-75.42	75.42	331.9
OTM-038	12-Oct-2005 05:57	ME	-1.5	14.829	12.95	-10.26	91.57	-56.73	59.11	92.8
OTM-039	21-Oct-2005 14:58	RCS	-2.1	0.090	223.65	-7.21	-80.92	-87.14	87.14	98.7
OTM-041	31-Oct-2005 13:59	ME	-0.8	12.416	22.74	-3.51	19.82	-66.97	69.26	77.6
OTM-042	13-Nov-2005 14:02	ME	-2.8	2.128	322.48	7.70	25.63	-24.31	26.98	13.2
OTM-043	23-Nov-2005 13:03	RCS	-0.8	0.060	248.74	11.33	-77.35	-70.67	70.67	64.8
OTM-044	28-Nov-2005 04:15	RCS	-0.8	0.237	4.26	-19.25	93.26	-47.66	47.66	269.8
OTM-047	30-Dec-2005 02:47	RCS	-1.5	0.183	63.72	67.17	16.76	-114.98	114.98	205.7
OTM-051	02-Feb-2006 07:53	RCS	-1.8	0.186	55.94	-28.85	-42.78	-93.89	93.89	210.4
OTM-053	02-Mar-2006 05:51	RCS	-0.8	0.265	235.13	24.63	112.21	-83.51	83.51	300.8
OTM-056	22-Mar-2006 04:19	ME	-1.2	0.467	267.65	4.11	-40.55	-44.34	45.44	2.8
OTM-057	06-Apr-2006 03:32	ME	-1.8	0.370	126.14	-0.77	8.26	-158.97	159.31	2.3
OTM-058	27-Apr-2006 01:59	RCS	-2.1	0.075	70.19	-4.70	100.43	-118.78	118.78	54.3
OTM-059	04-May-2006 01:28	ME	-0.8	0.505	313.20	21.95	9.57	-40.67	41.99	3.0
OTM-061	18-May-2006 00:41	RCS	-1.8	0.118	170.40	4.14	68.00	-136.38	136.38	86.4
OTM-063	07-Jun-2006 23:24	ME	-1.8	1.923	60.67	41.72	-106.10	-115.93	117.57	12.1
OTM-064	28-Jun-2006 22:07	RCS	-1.8	0.068	221.76	26.12	-49.66	-98.74	98.74	48.4

* Coordinated universal time (UTC) / spacecraft event time (SCET).
† OD data cutoff time (DCO) given in days relative to maneuver epoch.

The next subsections describe the maneuvers performed or cancelled during each encounter arc from 03-Aug-2005 to 28-Jun-2006. For a performed maneuver, the design ΔV and burn type are given in parentheses next to the maneuver name (e.g., OTM-026 (2.628 m/s, ME)). Trajectory deviations from the reference trajectory are measured relative to Saturn center. Downstream ΔV costs (penalties) are measured in a

[e]Spacecraft is Earth-pointed prior to each maneuver for spacecraft health and safety verification, for uplinking of the maneuver, and for acquisition of the 2-way Doppler before the maneuver.

deterministic sense, meaning statistical components are not included in the cost. The last maneuver considered in the cost and the corresponding encounter are also given (e.g., downstream ΔV through OTM-036 (to D1)).

A. Enceladus-2 (E2) to Titan-6 (T6) Flyby: OTM-026, OTM-027, and OTM-028

After the E2 flyby on 14-Jul-2005, two Titan encounters reduced the orbit inclination to near Saturn's equator, in preparation of the Hyperion, Dione, and Rhea flybys. The first of these Titan flybys was T6 on 22-Aug-2005. OTM-026 (2.628 m/s, ME) was performed on 03-Aug-2005, 20 days after the E2 flyby and one day before pericrone. The OTM-026 design ΔV was close to the 050720 reference trajectory value of 2.664 m/s. It was designed in an optimization chain with downstream maneuvers through OTM-036 (to D1). OTM-027 (2.418 m/s, ME), an apocrone maneuver executed on 10-Aug-2005, was also close to the 050720 reference trajectory value of 2.482 m/s. This maneuver left a B-plane error of $\approx$10 km. Although it came at nearly a 1 m/s ΔV cost (through OTM-036), OTM-028 was cancelled primarily to save on workforce.

B. Titan-6 (T6) to Titan-7 (T7) Flyby: OTM-029, OTM-030, and OTM-031

Finishing what T6 started, the T7 flyby placed Cassini in a Saturn equatorial orbit. This was mainly accomplished through the executions of OTM-029 and OTM-030. OTM-029 (1.459 m/s, ME) was designed in a T6-T8 8-maneuver optimization chain. It was performed on 25-Aug-2005, three days after the T6 encounter. This was an excellent example of asymptote control since performing only OTM-030 would have resulted in an $\approx$2 m/s bias in OTM-032, the T7 cleanup maneuver. OTM-030 (14.350 m/s, ME), performed near apocrone on 30-Aug-2005, was close to the 050720 reference trajectory value of 14.872 m/s. Finally, OTM-031 (0.063 m/s, RCS), the final targeting maneuver to T7, was performed four days prior to the T7 flyby on 03-Sep-2005. This was the first RCS burn since OTM-022, which was performed five months before. Although the T7 flyby would have been achieved if this OTM was cancelled, the downstream ΔV penalty through OTM-039 (to T8) of $\approx$5 m/s would have been too great to absorb.

C. Titan-7 (T7) to Hyperion-1 (H1) Flyby: OTM-032, OTM-033, and OTM-034

Although the OTM-032 prediction statistics are in the ΔV range of an ME burn, the great accuracy of the T7 flyby (only $\approx$150 meters off target) brought down the OTM-032 design into the RCS ΔV range. It was found that if OTM-032 was skipped, the downstream ΔV penalty through OTM-042 (to R1) was only $\approx$120 mm/s. Therefore, OTM-032 was cancelled and replaced by OTM-033 to target to the H1 encounter. OTM-033 (27.910 m/s, ME) was performed six days before the H1 flyby on 19-Sep-2005, the largest maneuver executed in the second year of the Saturn tour. It had a large deterministic component of 27.905 m/s (050720 reference trajectory) in order to achieve the Hyperion and Dione flybys. Following OTM-033, it was predicted that the H1 flyby error would be nearly 30 km. Due to Hyperion's low GM, this flyby error would not have incurred a sizable downstream ΔV cost and only increased the downstream trajectory deviation from the reference trajectory by about 50 km at most. In fact, the size of OTM-035, the H1 cleanup maneuver, actually reduced in size with the flyby error and a ΔV of $\approx$0.5 m/s through OTM-045 (to T9) was predicted to be saved. In addition, there was an $\approx$3 km ephemeris uncertainty of Hyperion since this would be the first close flyby of the icy satellite. Reduced to a pointing update issue, OTM-034 was cancelled by performing a pointing update.

D. Hyperion-1 (H1) to Dione-1 (D1) Flyby: OTM-035, OTM-036, and OTM-037

Following the first Hyperion flyby on 26-Sep-2005, another first flyby was achieved with Dione on 11-Oct-2005. Because the H1 to D1 trajectory was nearly ballistic, only one targeting maneuver was necessary, OTM-035 or OTM-036. Since performing OTM-036 would have been a larger maneuver at almost 0.5 m/s, it was decided to perform OTM-035 instead to meet the D1 flyby conditions and to allow more time for another maneuver if necessary. OTM-035 (0.295 m/s, RCS) was performed three days after the H1 flyby on 28-Sep-2005, resulting in an $\approx$10 km D1 flyby error. Since OTM-036 was cancelled following the nominal execution of OTM-035, OTM-037 was next considered to achieve the D1 flyby conditions. Like OTM-034 for the H1 flyby, OTM-037 was cancelled because the flyby error did not result in a downstream ΔV penalty through OTM-048 (to T10).

E. Dione-1 (D1) to Titan-8 (T8) Flyby: OTM-038, OTM-039, and OTM-040

In order to reach Rhea, Cassini needed to flyby Titan beforehand in order to achieve the necessary ΔV. Since the normal three days after a flyby cleanup maneuver location would have made the size of OTM-038 unacceptable and since Dione would not affect the OD solution significantly, OTM-038 was performed less than one day after the D1 flyby on 12-Oct-2005. OTM-038 (14.829 m/s, ME), designed before the D1 flyby, was targeted directly to the T8 encounter conditions and was close to the 050720 reference trajectory value of 14.789 m/s. In case OTM-038 failed, there were two backup locations made, one more than usual. After a study of performing either OTM-039 or OTM-040 to cleanup the ≈60 km T8 flyby error left by OTM-038 which would have resulted in a 26 m/s ΔV cost through OTM-048 (to T10), it was opted to perform OTM-039 and to use OTM-040 if necessary. Since the execution of OTM-039 (0.090 m/s, RCS) on 21-Oct-2005 yielded a T8 flyby error of less than 1 km, OTM-040 became too small to perform (< 7 mm/s) and was subsequently cancelled.

F. Titan-8 (T8) to Rhea-1 (R1) Flyby: OTM-041, OTM-042, and OTM-043

OTM-041 (12.42 m/s, ME), executed three days after the T8 flyby on 31-Oct-2005, was the first of two trajectory shaping maneuvers to achieve the R1 flyby. It was close to the 050720 reference trajectory value of 12.423 m/s. OTM-041 was designed in an optimization chained strategy up to OTM-051 (to T11). The Rhea targeting maneuver, OTM-042 (2.128 m/s, ME), was performed on 13-Nov-2005 near apocrone. This maneuver was also near the 050720 reference trajectory value of 2.085 m/s. A rather large R1 flyby error of ≈20 km was a result of the OTM-042 execution. Since the downstream ΔV penalty through OTM-057 (to T13) was deemed too high at ≈1.2 m/s, OTM-043 (0.060 m/s, RCS) was performed on 23-Nov-2005, three days before the R1 encounter. Most of this ΔV cost was found at OTM-044.

G. Rhea-1 (R1) to Titan-9 (T9) Flyby: OTM-044, OTM-045, and OTM-046

OTM-044 (0.237 m/s, RCS) was performed on 28-Nov-2005, one day after the Rhea encounter. Due to the short separation between maneuvers, OTM-044 had been prepared as an ME burn prior to the Rhea flyby. Based on the nominal execution of OTM-043, only OTM-044 was supposed to achieve the T9 flyby (i.e., OTM-045 was to be lumped onto OTM-044 in a deterministic sense). Lumping OTM-044 into OTM-045 was out of the question since it entailed an ≈4 m/s ΔV penalty. OTM-044 estimates based on pre-Rhea OD solutions held steady at ≈210 mm/s, changing it to an RCS maneuver, with no noticeable downstream ΔV penalty. OD solutions based on post-Rhea tracks changed the situation rather significantly. As in previous first time flybys of a satellite, there was a sizable ephemeris error in Rhea. OTM-044 grew to 385 mm/s, making it larger than either the largest RCS maneuver-to-date (OTM-004) or the smallest ME maneuver-to-date (OTM-025). In addition, there was a downstream penalty of ≈185 mm/s. Switching back to ME was considered, but required major changes in the maneuver configuration. Instead, the Navigation team decided that the most reliable change was to switch back to the chained 2-maneuver strategy (through OTM-057), bringing OTM-044 back down to the RCS range of 237 mm/s. Although OTM-044 was targeted to an intermediate aimpoint determined by the optimization chain strategy, OTM-045 and OTM-046 were cancelled since their respective sizes were small, the downstream ΔV penalty through OTM-57 (to T13) was only ≈0.25 m/s, and the flyby difference at T9 was acceptable (≈10 km).

H. Titan-9 (T9) to Titan-10 (T10) Flyby: OTM-047, OTM-048, and OTM-049

Since OTM-045 and OTM-046 had been cancelled, OTM-047 was not a candidate for cancellation. OTM-047 (0.183 m/s, RCS) was executed on 30-Dec-2005, three days after the T9 flyby. OTM-048 was the first of three apocrone maneuvers to be deleted beforehand in this portion of the tour (see the next section "V. Maneuver Deletions" for a discussion on the deleted maneuvers). Because OTM-047 left only an ≈1 km flyby error at T10, the design of OTM-049 fell below 1 mm/s, with no downstream penalty if skipped. Hence, OTM-049 was cancelled since it was too small to perform and implement.

I. Titan-10 (T10) to Titan-11 (T11) Flyby: OTM-050, OTM-051, and OTM-052

Three maneuver strategies were explored for T11 targeting, the nominal strategy of performing OTM-050 and OTM-051, performing OTM-050 only, and performing OTM-051 only. Comparing downstream ΔV costs up to OTM-063 (to T15), it was found that performing only OTM-051 would yield just an additional 0.15 m/s cost from the nominal strategy, whereas performing only OTM-050 would cost almost 2 m/s. Performing only OTM-051 would also keep the current trajectory closer to the reference trajectory. Hence, OTM-050 was cancelled in favor of OTM-051. Interestingly, OTM-050 marked the first time three maneuvers were cancelled consecutively. OTM-051 (0.186 m/s, RCS) was performed on 02-Feb-2006, near apocrone. The 2006-01 execution error model was first reported during the design of OTM-052. OTM-052 was ultimately cancelled since the T11 flyby error would only be a few kilometers, the size of OTM-052 was small, and the downstream ΔV penalty through OTM-063 (to T15) was negligible.

J. Titan-11 (T11) to Titan-12 (T12) Flyby: OTM-053, OTM-054, and OTM-055

OTM-053 (0.265 m/s, RCS) was executed on 02-Mar-2006, three days after the T11 encounter. Similar to the T9 to T10 encounter arc, OTM-053 brought the T12 flyby within about 1 km of the targeted aimpoint. Like OTM-048, the apocrone maneuver OTM-054 was deleted beforehand (see the next section "V. Maneuver Deletions" for an explanation). It was found that performing OTM-055 would actually save $\approx$0.7 m/s in downstream ΔV through OTM-063 (to T15), but was too small perform at around 9 mm/s. Two options were explored to inflate OTM-055 to a size greater than the 10 mm/s limit: 1) bias the T12 target time by 0.5 sec (OTM-055 increased to 0.0159 m/s) or 2) perform the OTM-055 backup (OTM-055-BU) (OTM-055 increased to 0.0125 m/s). In the end, OTM-055 was cancelled since the ΔV cost was deemed acceptable. However, canceling OTM-055 guaranteed that either OTM-056 or OTM-057 would have to be performed.

K. Titan-12 (T12) to Titan-13 (T13) Flyby: OTM-056, OTM-057, and OTM-058

The nominal strategy of performing OTM-056 and OTM-057 was kept since the cost of performing only OTM-057 would accrue a cost of $\approx$1.4 m/s in deterministic ΔV. In addition, the trajectory deviations would have increased to about 1500 km at one point before the T12 encounter. Hence, OTM-056 and OTM-057 were required. OTM-056 (0.467 m/s, ME) was executed on 22-Mar-2006, designed in an optimization chain with maneuvers through OTM-063 (to T15). OTM-057 (0.370 m/s, ME) was performed on 06-Apr-2006 near apocrone to target the T13 flyby. Incidently, OTM-057 was the smallest designed ME burn ever performed. The 060323 reference trajectory was first implemented with the OTM-057 target. Although the OTM-058 design ΔV was relatively small, it was not a candidate for cancellation. The ΔV cost through OTM-069 (to T17) grew to $\approx$5.5 m/s, with OTM-059 accounting for most of the ΔV hit. Additionally, the trajectory deviation from the reference trajectory would grow to over 1000 km during the T13 to T14 encounter leg. Therefore, OTM-058 had to be executed. OTM-058 (0.075 m/s, RCS) was performed three days before the T13 encounter, bringing the flyby error to under 2 km.

L. Titan-13 (T13) to Titan-14 (T14) Flyby: OTM-059, OTM-060, and OTM-061

Since OTM-060 was deleted beforehand (see the next section "V. Maneuver Deletions"), OTM-059 (0.505 m/s, ME) was necessary. OTM-059 was performed on 04-May-2006 as a targeting maneuver to the T14 encounter. To cleanup the T14 flyby error left by OTM-059, OTM-061 (0.118 m/s, RCS) was executed on 18-May-2006. It could not be cancelled because leaving the flyby error would have resulted in an $\approx$9 m/s downstream ΔV penalty through OTM-072 (to T18). The large asymptote error at T14 would have increased OTM-062 by $\approx$4 m/s and OTM-063 by $\approx$2.5 m/s, and trickled down to the T15 cleanup, OTM-064, with an added $\approx$2.5 m/s. On top of that, the maximum trajectory deviation from the reference trajectory in the T14 to T15 encounter leg would have jumped from 100 km to 5500 km.

M. Titan-14 (T14) to Titan-15 (T15) Flyby: OTM-062, OTM-063, and OTM-064

Since OTM-062 could not be performed or implemented with a ΔV under 1 mm/s, it was cancelled. OTM-063 (1.923 m/s, ME) was executed near apocrone on 07-Jun-2006, targeted to the T15 flyby conditions. To correct the OTM-063 delivery to T15, OTM-064 (0.068 m/s, RCS) was performed on 28-Jun-2006, three days before the T15 encounter. If OTM-064 was cancelled, the ΔV cost would have been $\approx$3 m/s through OTM-075 (to T19), paid almost all upfront with OTM-065. Also, the trajectory deviation would have been much greater following the T15 flyby.

VI. Maneuver Deletions

After the R1 flyby on 26-Nov-2005, only alternating inbound and outbound Titan encounters were targeted through July 2006. The Titan encounters were T9 (outbound), T10 (inbound), T11 (outbound), T12 (inbound), T13 (outbound), T14 (inbound), and T15 (outbound). Spacing between the inbound-to-outbound encounters were 43 days and the outbound-to-inbound 20 days. Since the cleanup and apocrone OTMs were separated by only 4 days for the outbound-to-inbound Titan transfers, little time was allowed to reach converged OD solutions for the apocrone maneuver designs. It was proposed that the second maneuvers in the outbound-to-inbound transfers (OTM-048, OTM-054, and OTM-060) could be effectively deleted. This was supported by the fact that the deterministic components of these maneuvers decreased to only a few mm/s with the 050720 reference trajectory, as opposed to $\approx$0.3 to $\approx$1.0 m/s values reported in the Navigation Plan.[8] The ΔV statistics of OTM-047 through OTM-064 were studied for two cases using LAMBIC: the nominal chained maneuver strategy with all maneuvers performed and a chained maneuver strategy with OTM-048, OTM-054, and OTM-060 eliminated from the list of maneuvers. Comparing the two maneuver strategies revealed that there was only a minor change to the mean ΔV of $\approx$1 m/s and the $\Delta V95$ penalty was only 2.3 m/s. Based on this analysis which was conducted in November 2005, OTM-048, OTM-054, and OTM-060 were deleted from the maneuver schedule.

VII. Maneuver Cancellation Process

Since arriving at Saturn in July 2004, the minimum OD uncertainty size (semi-major axis) for approach maneuvers had been lowered from 10 km to 5 km, and then to 3 km (since OTM-047). Similarly, the maneuver execution error uncertainties have been reduced by more than half with the 2006-01 execution error model (since OTM-053). These reductions are a consequence of the better than expected accuracy of the maneuvers performed by Cassini, resulting in more maneuver cancellations than anticipated. With the rate of maneuver cancellations increasing to 1 out of 3 maneuvers during the second year of the tour, streamlining the maneuver cancellation process became a top priority. Here is the "cancellation checklist" that was considered by the Navigation team to assess a maneuver's candidacy for cancellation (discussed in further detail in the next subsection):

- Is the maneuver too small to perform? (YES if $\Delta V < 10$ mm/s)
- Is the total downstream ΔV cost acceptable if the maneuver is cancelled? (Usually YES if total downstream ΔV cost ≥ 1.0 m/s)
- Are the changes to the next target asymptote acceptable? (YES if RA/DEC asymptote differences $\leq$ LAMBIC 2-σ values)
- Are the trajectory deviations without the maneuver acceptable? (Depends on science pointing requirements for each satellite and Saturn.)
- Is the B-plane target correction with the approach maneuver significant? (YES if there is a distinct separation of the OD and approach maneuver delivery ellipses.)

Because of the frequency of maneuver cancellations, the generation of downstream ΔV comparisons (deterministic ΔV comparisons from SEPV output), downstream ΔV penalty contour and surface plots, trajectory deviation plots, and other tools for answering the above questions were automated with each maneuver design. This automation follows the design philosopy outlined in Ref. 16.

A. Maneuver Cancellation Checklist

1. Is the maneuver too small to perform?

For Cassini, a maneuver size of less than 10 mm/s was deemed as too small to perform and a maneuver size of less than 1 mm/s too small to implement in the maneuver sequencing commands. During the second year of the Saturn tour, there were four instances when maneuvers were too small to perform or implement: OTM-040 (< 7 mm/s), OTM-049 (<1 mm/s), OTM-055 (< 9 mm/s), and OTM-062 (< 1 mm/s). A maneuver being to small to perform, however, is not always the sole basis to cancel the maneuver. For example, although OTM-055 was too small to execute, cancelling it would cost about 0.7 m/s in downstream ΔV. For this case, options for inflating the maneuver to over the 10 mm/s limit were explored, even though the maneuver was later cancelled and the ΔV was accepted.

2. Is the total downstream ΔV cost acceptable if the maneuver is cancelled?

Throughout the frequent cancellation meetings, 1 m/s became one of the metrics for deciding if the downstream ΔV costs would be too great to absorb if the maneuver was cancelled (i.e., the maneuver is required if the total downstream ΔV cost $\geq$ 1 m/s). Of course, other factors were considered in conjunction with the downstream cost: individual downstream ΔV increases and the effect on the workforce. The downstream ΔV penalties have been determined by two different methods: comparing the downstream deterministic ΔVs (from SEPV) and generating downstream ΔV penalty contour and surface plots at the B-plane of the upcoming encounter (see next subsection).

For approach maneuvers, usually the downstream ΔVs resulting from performing the maneuver and from cancelling the maneuver are compared to compute the downstream cost. For cleanup maneuvers, three different scenarios are often explored: perform both the cleanup and apocrone maneuver, perform the cleanup maneuver only, and perform the apocrone maneuver only. Finally, for apocrone maneuvers, three cases are usually studied: perform the apocrone maneuver only, perform the approach maneuver only, and cancel both the apocrone and approach maneuver.

Total downstream ΔV penalties under 1 m/s resulted in the cancellations of OTM-034, OTM-037, OTM-045, OTM-049, and OTM-052. Total downstream ΔV costs greater than and equal to 1 m/s were the main deciding factors for not cancelling OTM-043, OTM-056, OTM-058, OTM-061, and OTM-064.

3. Are the changes to the next target asymptote acceptable?

Cancelling a maneuver usually has some effect on the incoming asymptotes to the downstream encounters. Especially with a cancelled approach maneuver, the next encounter after the upcoming flyby may have incurred a sizable difference in the asymptote direction. The criteria of the right ascension and the declination differences being $\leq$ the predicted 2-σ values (from LAMBIC) has been used in determining if an asymptote change is within expectations.

4. Are the trajectory deviations without the maneuver acceptable?

The reference trajectory provides the spacecraft orbital path. Trajectory deviations from the reference trajectory occur due to OD and maneuver execution errors. These deviations are controlled at the targeted encounter aimpoints (i.e., there are no position differences at the flyby times), but grow following a maneuver and become magnified at pericrones. Usually cancelling a maneuver causes the trajectory deviations to grow larger, possibly affecting future science instrument pointing. Of course, this is a case-by-case issue depending on the science pointing requirements for each satellite and Saturn. Since the sequence design is based on the reference trajectory, if the trajectory deviation becomes too large, data might be lost or require alterations to the sequence (i.e., a pointing update).

5. Is the B-plane target correction with the approach maneuver significant?

Since the approach maneuver is the last maneuver before an encounter, the target correction from the maneuver is usually explored. The cumulative probability density function of the B-plane miss magnitudes of the OD delivery ellipse (which can represent a cancelled approach maneuver delivery) and the approach maneuver delivery ellipse are compared against the desired B-plane correction. If the curves are largely separated, it verifies that the maneuver will make a measurable change in the flyby aimpoint. If the curves are overlapping most of the time, it indicates that the maneuver will not make a change larger than the OD error in the target location, leading to a maneuver cancellation decision.

B. Downstream ΔV Penalty Contour and Surface Plots

Contour and surface plots of the downstream ΔV costs are useful in visualizing the ΔV cost range for given OD and maneuver deliveries. Throughout the tour, downstream ΔV penalty plots have been studied for approach maneuver cancellation considerations. Recently, this has been extended to determining if a cleanup maneuver can be cancelled, even before the flyby has been achieved.

Since an approach maneuver is the last correction before a flyby, there is a well-defined target aimpoint. The sum of the chained downstream maneuvers are computed for each grid point (i,j) representing a flyby error in $\mathbf{B}\cdot\mathbf{R}$ and $\mathbf{B}\cdot\mathbf{T}$ via LAMBIC (defined as $\sum_1$). Contours and surfaces are plotted with the Δ relative to the nominal flyby point $\sum_1$(i,j) - $\sum_1$(0,0), see figure 4, since a linear approximation technique tends to be more accurate in computing a difference rather than the (sub)total cost. Hence, a zero-cost contour always passes through the origin. For an approach maneuver, the contour and surface ΔV penalty plots provide a graphical approximation to downstream penalty for a given miss from the nominal flyby aimpoint. This penalty assumes implementation of a flyby cleanup maneuver.

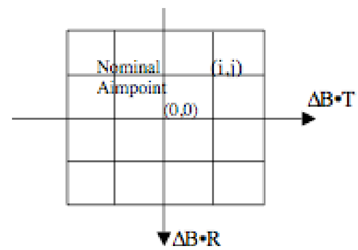


Figure 4. ΔV Contour

A flyby cleanup maneuver, however, does not have a well-defined B-plane target. Hence, it is more convenient to reference the cost of the cleanup maneuver cancellation to the previous flyby. When cleanup and apocrone maneuvers are designed, the shifts in the target B-plane are plotted together for convenience even though there are three separate B-planes. If a cleanup maneuver has a small deterministic component, LAMBIC can be also set up to compute the ΔV sum over the same set of grid points, while skipping the post flyby cleanup maneuver (defined as $\sum_2$). In this case, plotting $\sum_2$(i,j) - $\sum_2$(0,0) represents a different class of ΔV contour, like deletion rather than possible cancellation. For each grid point (i,j), it is the difference $\sum_2$(i,j) - $\sum_1$(i,j) that approximates the penalty for canceling the flyby cleanup maneuver for a given flyby miss.

OTM-052, the approach maneuver to T11, was cancelled since there was a small downstream ΔV penalty. This is shown in figure 5, where the OD delivery ellipse is centered near the zero-contour line. OTM-061, the approach maneuver to T14, was performed although it had a small ΔV of ≈100 mm/s because the downstream ΔV was large. This can be seen in figure 6, where the OD delivery dispersion is centered near the 10 m/s penalty contour line. OTM-062, the T14 cleanup maneuver, was cancelled since it was too small to perform and sequence. It might have been cancelled at the time of the OTM-061 maneuver design if the contour cost shown in figure 7 was used as a basis.

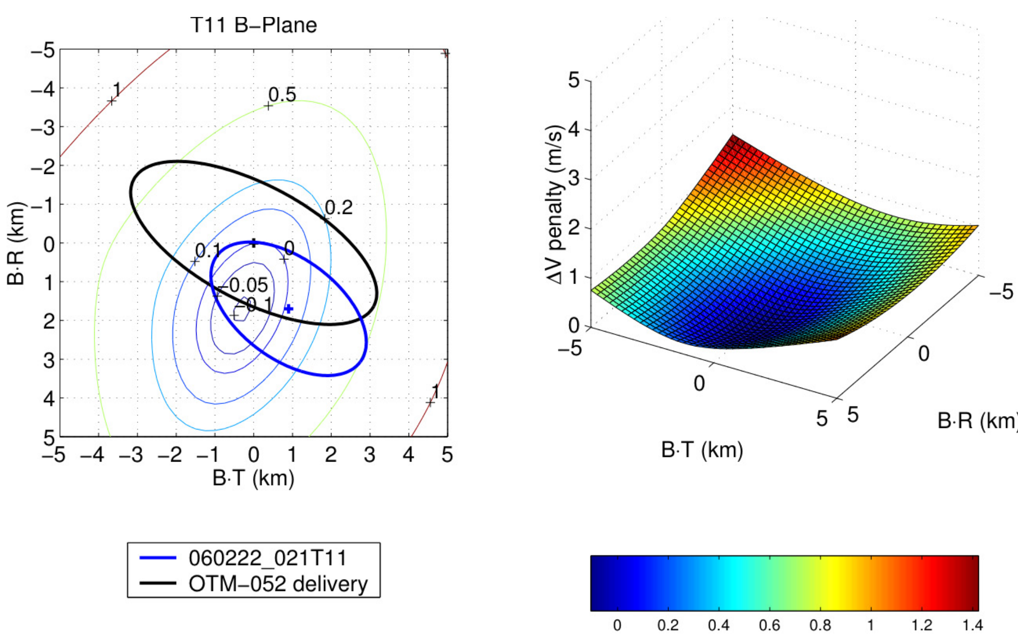


Figure 5. OTM-052 Cancellation Downstream ΔV Penalty Contour and Surface Plots

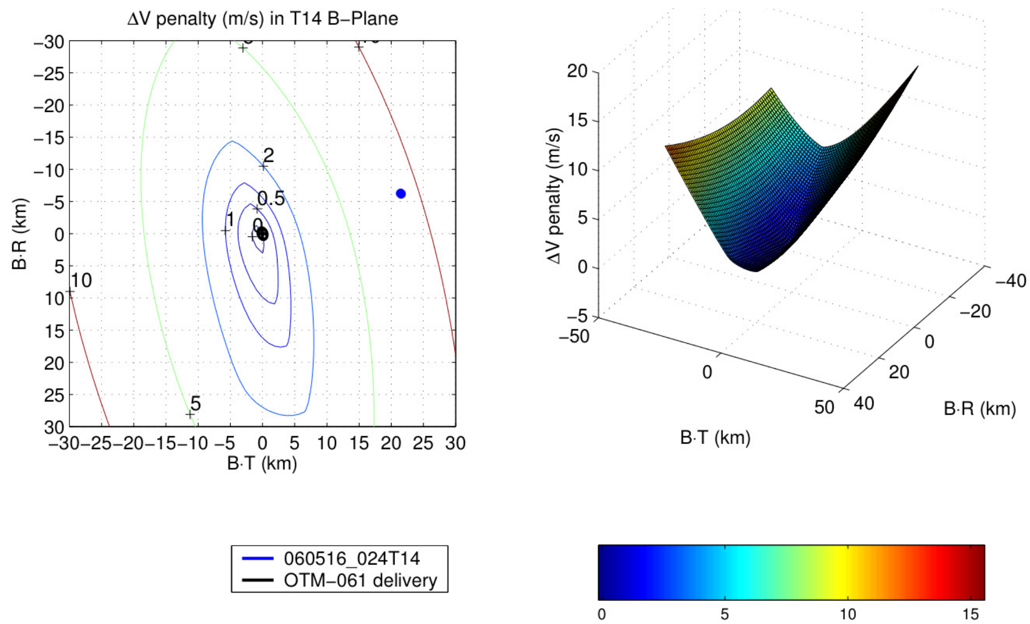


Figure 6. OTM-061 Cancellation Downstream ΔV Penalty Contour and Surface Plots

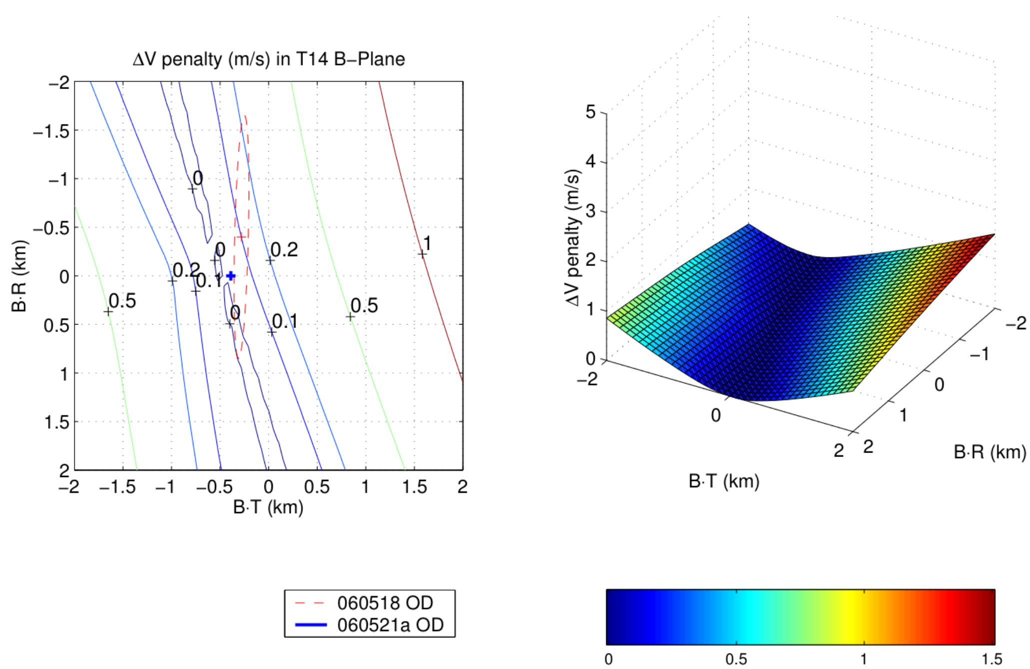


Figure 7. OTM-062 Cancellation Downstream ΔV Penalty Contour and Surface Plots

VIII. Maneuver Execution Error Model Estimation

In assembling the maneuver-execution error data that will be fitted, it may seem appropriate to just simply subtract the reconstructed ΔV from the design ΔV to obtain the maneuver execution error. However, this approach does not provide insight into the source of the error and may not be consistent with the orbit determination (OD).

One issue is there are events associated with each maneuver that, although they may not be part of the maneuver ΔV design, cannot be cleanly separated out in the OD process. As a result, the ΔV for each maneuver includes the design ΔV (burn and turns) plus any such ΔV events related to the maneuver (e.g., deadband tightening and limit cycling, Reaction Wheel Assembly (RWA) biasing, etc.). This ΔV (design ΔV plus associated ΔV events) will be herein referred to as the expected ΔV.

A second issue is the choice of coordinate system for expressing the errors. Since each maneuver ΔV is in a different inertial direction yet is controlled by the on-board cut-off algorithm and attitude control system, body-fixed coordinates are a natural choice for analyzing the execution errors. A spacecraft coordinate frame already exists for Cassini (see previous section "II. Maneuver Execution"). However, a coordinate system with an axis parallel to the expected ΔV is preferred. The compromise is the thrust-vector-control (TVC) coordinate frame with Z_{TVC} parallel to the expected ΔV, X_{TVC} parallel to the projection of $X_{S/C}$ into the plane perpendicular to Z_{TVC}, and Y_{TVC} completing the right-handed system. The plane perpendicular to Z_{TVC} is referred to herein as the pointing plane.[2] With this type of coordinate frame, the execution error can be expressed with two perpendicular components, magnitude and pointing. Magnitude errors are computed simply by differencing the lengths of the reconstructed and expected ΔV vectors. Pointing errors are the vector differences of the reconstructed and expected ΔVs projected onto the pointing plane. They are given in X_{TVC} and Y_{TVC} components in m/s as they represent ΔV errors. Use of angular units is reserved for the proportional component of the pointing errors.

A. Maximum Likelihood Estimator

The Gates-model parameters are determined herein with maximum-likelihood estimation. First, the probability density function (pdf) for the magnitude error is

$$f_m(x) = \left[2\pi(\sigma_1^2 + y^2\sigma_2^2)\right]^{-1/2} \exp\left[-\frac{1}{2}\frac{(x-\mu_m)^2}{\sigma_1^2 + y^2\sigma_2^2}\right] \tag{6}$$

where x is the magnitude error, μ_m is the mean magnitude error, y is the magnitude of the maneuver, σ_1 and σ_2 are the fixed and proportional Gates-model parameters for magnitude, and exp is the exponential function. Then, the likelihood is defined as the product of evaluations of $f_m(x)$ for each measurement:

$$L_m(\sigma_1, \sigma_2) = \prod_{i=1}^{N} f_m(x_i, y_i, \sigma_1, \sigma_2) \tag{7}$$

Likewise, for the pointing error, a two-dimensional vector, the pdf is

$$f_p(x) = \left[\sqrt{2}\pi(\sigma_3^2 + y^2\sigma_4^2)\right]^{-1} \exp\left[-\frac{1}{2}\frac{(x-\mu_p)^2}{\sigma_3^2 + y^2\sigma_4^2}\right] \tag{8}$$

where x is the length of the pointing error vector in units of speed, μ_p is the mean pointing error, y is the magnitude of the maneuver, and σ_3 and σ_4 are the fixed and proportional Gates-model parameters for pointing. The likelihood is then defined as follows:

$$L_p(\sigma_3, \sigma_4) = \prod_{i=1}^{N} f_p(x_i, y_i, \sigma_3, \sigma_4) \tag{9}$$

A weighted maximum-likelihood approach is constructed by raising each term in the likelihood function to a power. For the magnitude errors, the exponent is the inverse of the 1-σ uncertainty. For pointing errors, the uncertainty is two-dimensional, so the inverse of the standard deviation of the error along the pointing-error direction is used. The Gates-model parameters for magnitude errors are found by maximizing L_m; likewise for pointing errors L_p. Based on the form of these equations, only two measurements are required to determine the parameters. It follows then that with more measurements, more accurate estimates will be produced.

B. Maneuver Execution Errors

Most maneuvers performed from interplanetary cruise through OTM-044 were used in the determination of the 2006-01 maneuver execution-error model: specifically, 38 ME and 11 RCS maneuvers. Table 7 lists the execution errors (magnitude and pointing) of the ME and RCS maneuvers performed during the second year of tour. (See Ref. 3 for the cruise Trajectory Correction Maneuver (TCM) magnitude and pointing errors and Ref. 4 for the first year of Saturn tour OTM magnitude and pointing errors.)

Table 7. Maneuver Execution Errors (Magnitude and Pointing)

Maneuver	Maneuver Epoch (UTC/SCET)*	Burn Type	Expected ΔV† (m/s)	Magnitude: Mag. Error (mm/s)	Magnitude: 1-σ Uncert. (mm/s)	Pointing: X_{TVC} Error (mm/s)	Pointing: Y_{TVC} Error (mm/s)	Pointing: 1-σ Uncertainty: SMAA × SMIA, θ‡ (mm/s)
OTM-026	03-Aug-2005 11:50	ME	2.627	-6.53	2.67	-8.33	0.51	7.73 × 0.04, 87.7°
OTM-027	10-Aug-2005 13:21	ME	2.416	-1.08	3.10	-4.31	0.73	0.97 × 0.17, 61.3°
OTM-029	25-Aug-2005 17:08	ME	1.457	-5.92	2.58	-1.31	-2.22	1.86 × 0.22, 102.7°
OTM-030	30-Aug-2005 18:43	ME	14.348	6.36	4.25	-4.42	7.24	1.47 × 0.20, 70.6°
OTM-031	03-Sep-2005 17:30	RCS	0.062	1.18	0.39	-0.25	-0.10	3.86 × 0.27, 104.6°
OTM-033	19-Sep-2005 16:40	ME	27.903	21.52	0.55	-56.70	6.84	3.41 × 0.08, 88.5°
OTM-035	28-Sep-2005 16:11	RCS	0.299	0.70	0.55	4.12	-1.71	0.47 × 0.15, 79.0°
OTM-038	12-Oct-2005 05:57	ME	14.836	1.46	0.09	-12.43	-3.02	0.46 × 0.06, 79.3°
OTM-039	21-Oct-2005 14:58	RCS	0.092	0.26	0.67	3.49	-0.35	0.75 × 0.08, 97.8°
OTM-041	31-Oct-2005 13:59	ME	12.418	5.98	0.08	-20.11	3.39	1.35 × 0.03, 87.8°
OTM-042	13-Nov-2005 14:02	ME	2.137	-4.06	0.88	3.17	5.60	1.74 × 0.74, 167.3°
OTM-043	23-Nov-2005 13:03	RCS	0.064	0.84	0.57	-1.45	0.56	3.16 × 0.17, 85.9°
OTM-044	28-Nov-2005 04:15	RCS	0.241	3.32	0.10	1.51	-0.11	0.45 × 0.04, 79.1°
OTM-047	30-Dec-2005 02:47	RCS	0.182	-1.34	0.15	0.67	0.09	0.25 × 0.07, 88.0°
OTM-051	02-Feb-2006 07:53	RCS	0.186	-1.04	0.21	2.15	0.08	0.14 × 0.01, 89.6°
OTM-053	02-Mar-2006 05:51	RCS	0.265	-1.49	0.12	1.35	0.16	0.14 × 0.02, 90.0°
OTM-056	22-Mar-2006 04:19	ME	0.480	-0.87	0.14	0.96	3.53	0.19 × 0.09, 44.8°
OTM-057	06-Apr-2006 03:32	ME	0.362	-0.63	0.05	-1.01	4.23	0.17 × 0.12, 121.3°
OTM-058	27-Apr-2006 01:59	RCS	0.075	2.65	0.10	-0.88	-0.12	0.24 × 0.04, 99.2°
OTM-059	04-May-2006 01:28	ME	0.512	3.57	0.15	0.72	2.36	0.17 × 0.12, 17.0°
OTM-061	18-May-2006 00:41	RCS	0.113	2.46	0.22	-0.85	0.41	0.41 × 0.20, 80.9°
OTM-063	07-Jun-2006 23:24	ME	1.918	-5.33	0.08	-0.90	6.40	0.10 × 0.04, 84.0°
OTM-064	28-Jun-2006 22:07	RCS						

* Coordinated universal time (UTC) / spacecraft event time (SCET).

† The expected ΔV magnitude includes the design ΔV (burn and turns) plus all ΔV events related to the maneuver (e.g., deadband tightening, Reaction Wheel Assembly (RWA) / RCS transitions, etc.).

‡ 1-σ pointing uncertainty numbers are 1-σ ellipse dimensions (semi-major axis (SMAA) × semi-minor axis (SMIA)) with orientation angle, θ (relative to pointing plane X_{TVC} axis).

IX. 2006-01 Maneuver Execution-Error Model

Because of the continued sub-σ errors seen in the executions of the main engine and RCS, interest again surfaced to modify the maneuver execution-error model. Using maneuvers performed from cruise up to OTM-044 in November 2005, a less conservative execution-error model was developed (see Refs. 11 and 12). This model, designated 2006-01, has been in use since March 2006. The next subsections summarize the analysis that was conducted in the determination of the 2006-01 execution-error model and present a side-by-side comparison of models used during the Cassini-Huygens mission.

A. 2006-01 Execution-Error Study

Figures 8 and 9 show magnitude error as a function of maneuver magnitude for the RCS and main engine maneuvers, respectively, used in the 2006-01 study. The error bars show the 1-σ uncertainties in the OD estimates of the magnitude errors. These uncertainties were used to weight each maneuver in the maximum-likelihood estimator. The red dashed lines in the figures indicate the magnitude-error biases as functions of ΔV magnitude which were computed using the fixed- and proportional-magnitude biases from the study (see table 10). The red solid lines display the 1-σ bounds on the magnitude errors using the 2006-01 study execution-error model given in tables 8 and 9. All maneuvers considered within the 1-σ magnitude-error bounds are given red error bars. As seen in figure 8, the 1-σ magnitude errors of 8 out of 11 (72.7%) RCS maneuvers were within the 1-σ magnitude-error bounds ($\approx$68%), which is near the expected normal distribution of magnitude errors as a function of maneuver size. Likewise in figure 9, the 1-σ magnitude errors of 23 out of 38 (60.5%) main engine maneuvers were within the 1-σ magnitude-error bounds.

The percentage of samples that fall within the estimated standard deviation in each case support the idea that the distributions examined here, both main engine and RCS, are Gaussian. As such, it should be expected that the maximum-likelihood estimator can find a good fit to the data. The trends in the fit seem to be consistent with the data, the resulting model appears reasonable, and the model parameters match well with expectations. Hence, the 2006-01 model was considered an excellent execution-error model replacement.

Figures 10 and 11 show the 1-σ pointing error ellipses in the TVC pointing plane of the main engine and RCS maneuvers, respectively, from the new study. The pointing error ellipses are color-coded according to maneuver size (as indicated in the figures). For instance, in figure 11, OTM-010a is given the color magenta to show that it is between 0.1 and 0.2 m/s in size.

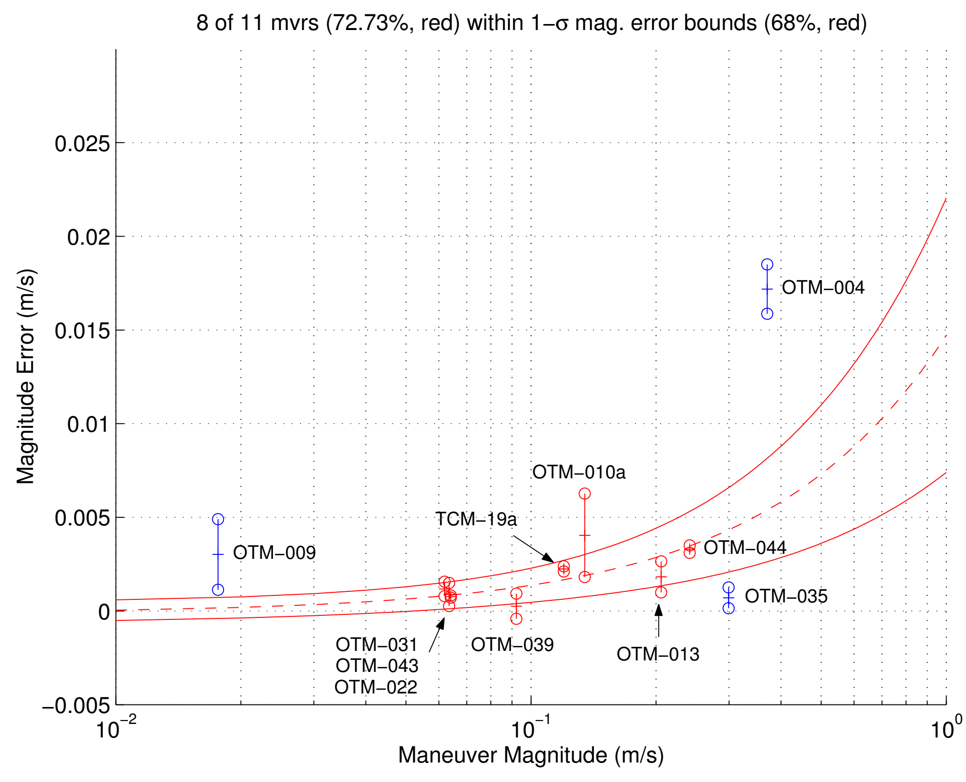
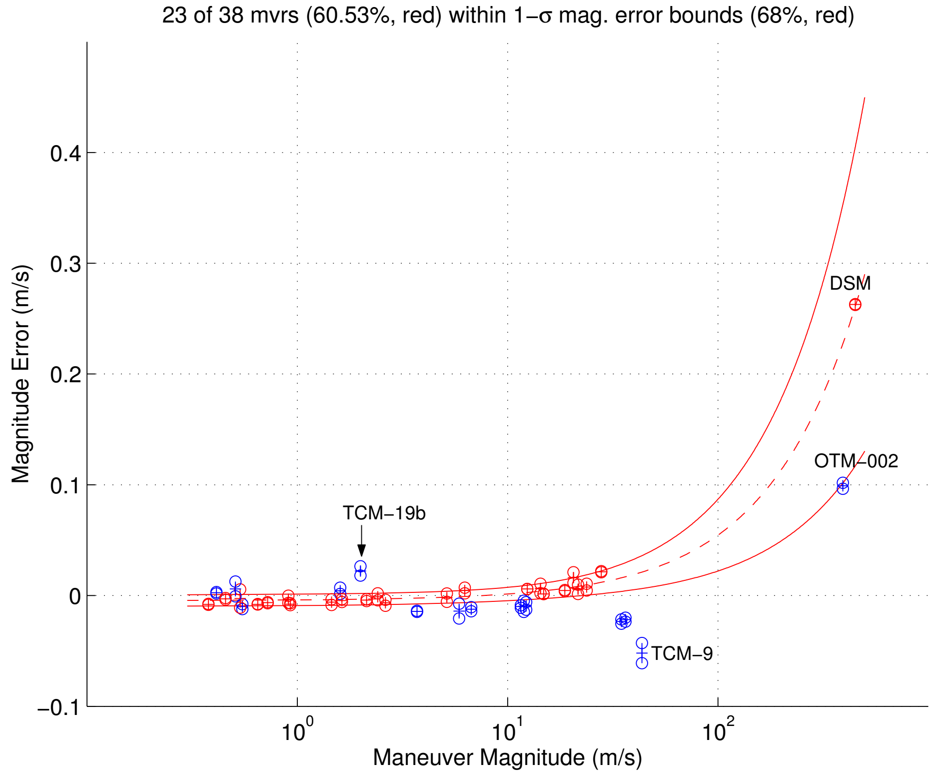
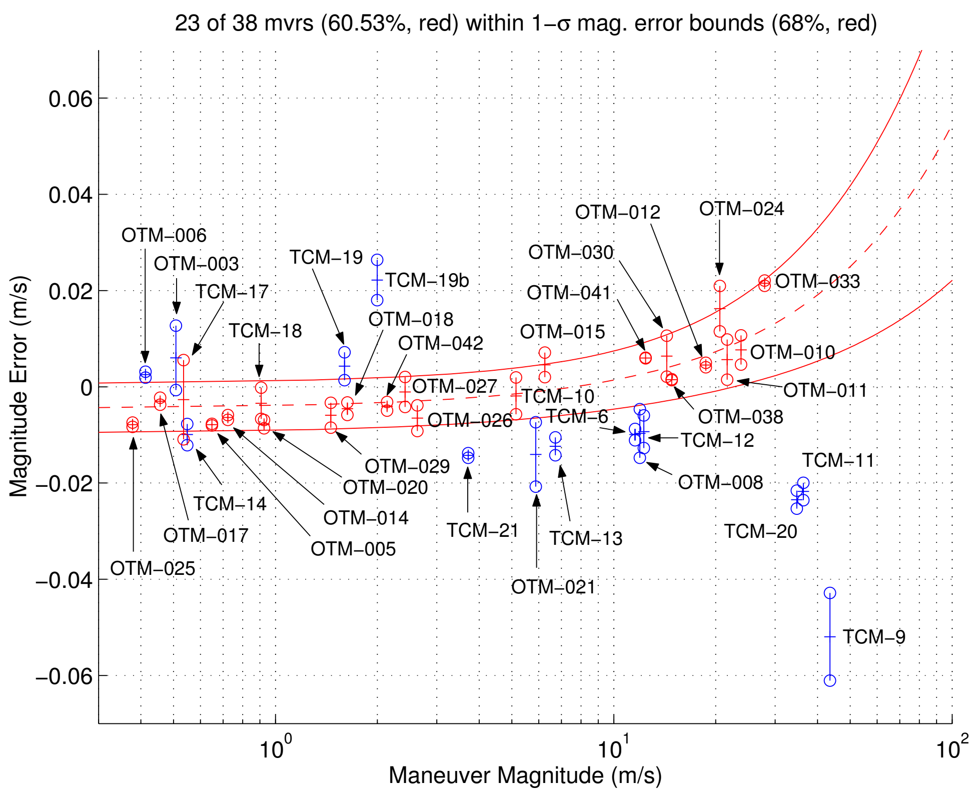


Figure 8. RCS Magnitude Errors. *Error bars show the 1-σ uncertainties, red dashed line the magnitude-error bias, and red solid lines the 1-σ magnitude-error bounds. All maneuvers considered within the 1-σ magnitude-error bounds are given red error bars.*

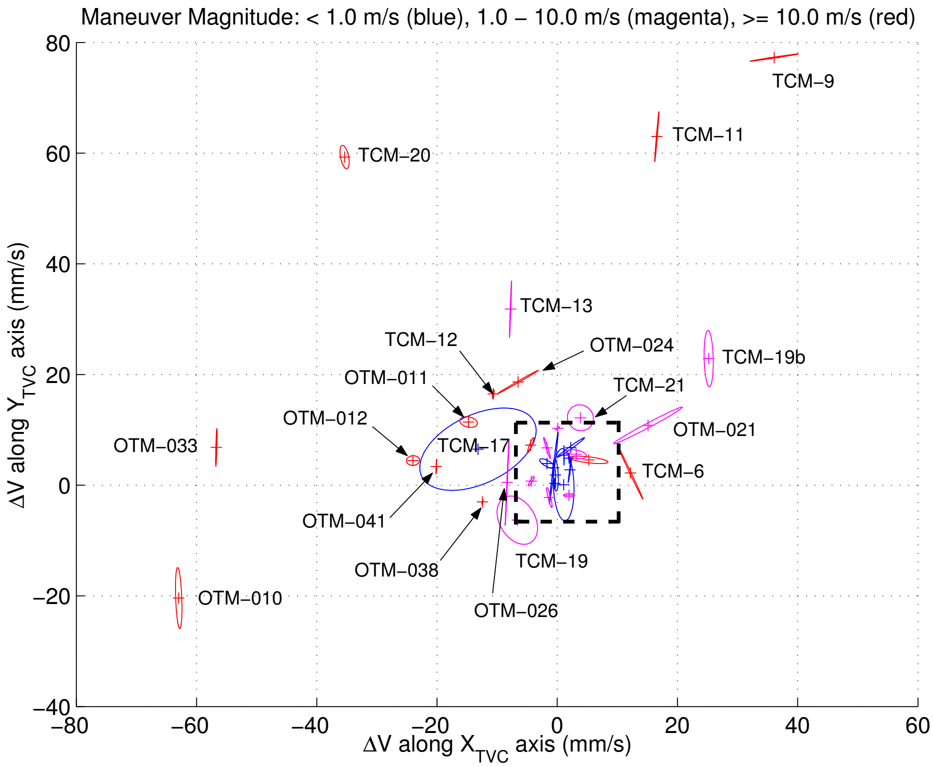


(a) Main Engine Maneuvers (Cruise through OTM-042)

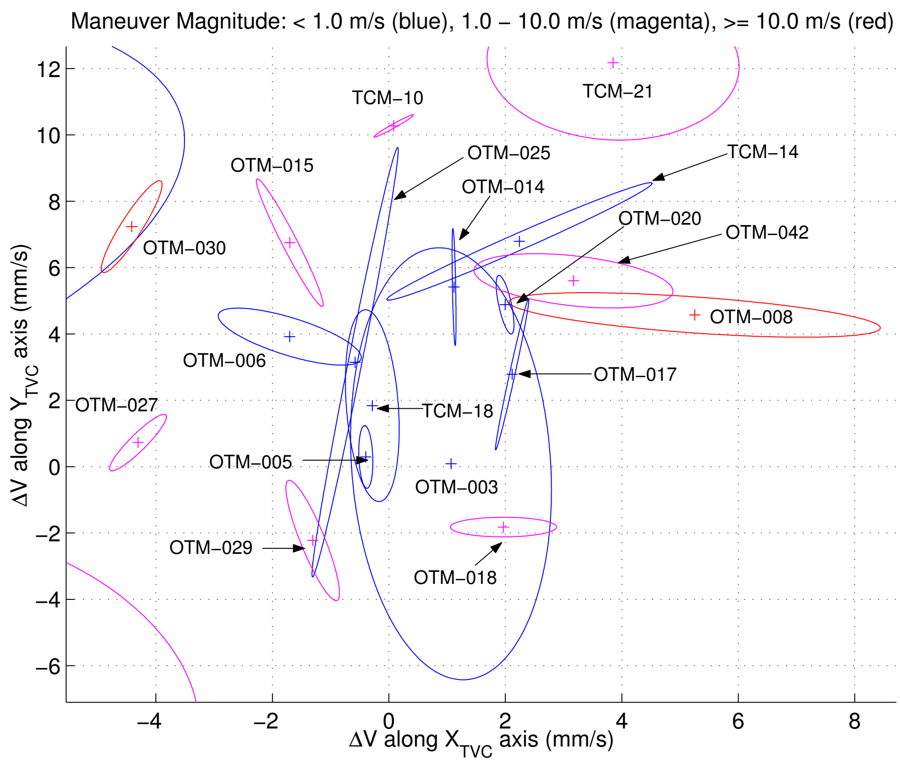


(b) Close-Up of Main Engine Maneuvers under 100 m/s

Figure 9. Main Engine Magnitude Errors. *Error bars show 1-σ uncertainties, red dashed lines the magnitude-error biases, and red solid lines the 1-σ magnitude-error bounds. All maneuvers considered within the 1-σ magnitude-error bounds are given red error bars.*



(a) Main Engine Maneuvers (Cruise through OTM-042)



(b) Close-Up of Dashed Box in (a)

Figure 10. Main Engine Pointing-Error Ellipses in Pointing Plane (1-σ). *DSM and OTM-002 are not shown since they are far from the origin.*

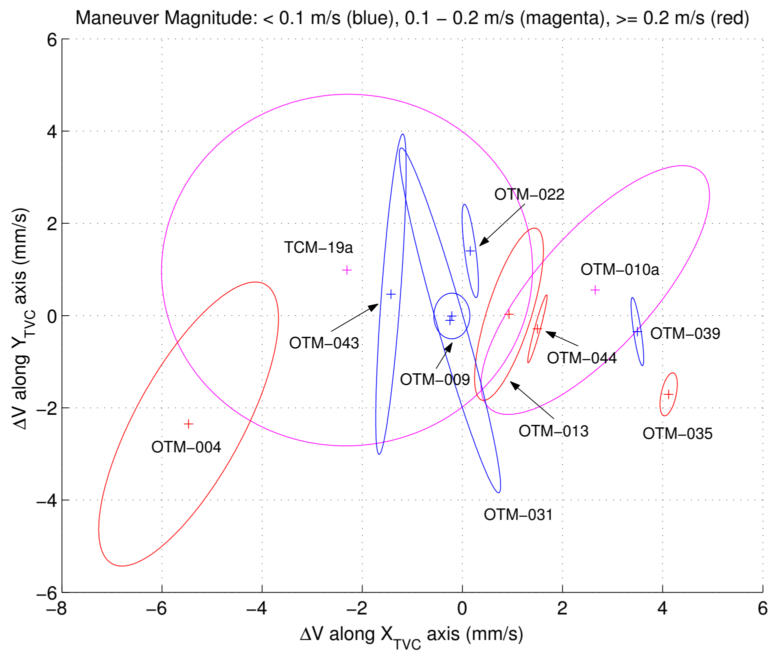


Figure 11. RCS Pointing-Error Ellipses in Pointing Plane (1-σ).

B. Execution-Error Model Comparisons

Tables 8 and 9 list the Gates execution error models for main engine and RCS that have been used since launch. The 2000 execution-error model was based on the analysis of maneuvers during early interplanetary cruise.[2] It had been used from April 2000 during cruise to February 2006 during the Saturn tour. The 2006-01 execution-error model has been used since March 2006 starting with the OTM-053 maneuver design. Building on the maneuvers that were a basis of the 2000 model, the 2006-01 model was developed utilizing maneuvers from cruise to November 2005 (38 ME and 11 RCS maneuvers). The 2006-01 study, which the 2006-01 model is based, assumes that all magnitude and pointing biases are removed from ME and RCS burns.

Table 8. Main Engine Execution-Error Models (1-σ)

		2000 Model[8, 10]	2006-01 Model[11]	2006-01 Study[12]
Magnitude	Proportional (%)	0.2	0.04	0.03
	Fixed (mm/s)	10.0	6.5	5.0
Pointing (per axis)	Proportional (mrad)	3.5	1.0	1.0
	Fixed (mm/s)	17.5	4.5	6.5

Table 9. RCS Execution-Error Models (1-σ)

		2000 Model[8, 10]	2006-01 Model[11]	2006-01 Study[12]
Magnitude	Proportional (%)	2.0	0.7	0.7
	Fixed (mm/s)	3.5	0.9	0.6
Pointing (per axis)	Proportional (mrad)	12.0	12.0	4.0
	Fixed (mm/s)	3.5	3.5	2.5

In the 2006-01 execution-error study, data were processed to remove magnitude and pointing biases from the error estimates. Table 10 shows the fixed and proportional components of the magnitude and pointing biases computed for both main engine and RCS maneuvers. The 2006-01 execution error model assumes only the proportional magnitude bias for RCS is removed. Once more of these biases are removed from the ME and RCS systems, a new execution-error model will emerge that will take these changes into account. (See Ref. 11 for the recommended action items for removing these biases.)

Table 10. Execution-Error Biases (2006-01 Study)

		Main Engine	RCS
Magnitude	Proportional (%)	0.06	1.5
	Fixed (mm/s)	-4.5	0.0
Pointing	Proportional (mrad)	0.3	7.5
(X_{TVC} axis)	Fixed (mm/s)	-9.0	0.8
Pointing	Proportional (mrad)	1.5	-4.5
(Y_{TVC} axis)	Fixed (mm/s)	-3.0	3.5

X. Closing

In its second year at Saturn, the Cassini-Huygens spacecraft has been navigated extremely successfully. This success is in great part due to the excellent maneuver performance of the spacecraft. Delivery accuracy at each targeted encounter has been stellar and as a consequence, over one-third of the planned maneuvers during the second year of tour were cancelled. Further refinement of the maneuver cancellation process will continue, as well as new analyses of the maneuver execution errors for possible model enhancements. With two more years of the nominal Saturn tour remaining and an extended mission projected to last at least two years, there will not be a shortage of maneuver experience to report in the future.

Appendix: B-Plane Description

Planet or satellite approach trajectories are typically described in aiming plane coordinates referred to as "B-plane" coordinates[17] (see figure 12). The B-plane is a plane passing through the target body center and perpendicular to the asymptote of the incoming trajectory (assuming two-body conic motion). The "B-vector", **B**, is a vector in that plane, from the target body center to the piercing-point of the trajectory asymptote. The B-vector specifies where the point of closest approach would be if the target body had no mass and did not deflect the flight path. Coordinates are defined by three orthogonal unit vectors, **S**, **T** and **R**, with the system origin at the center of the target body. The **S** vector is parallel to the spacecraft V_∞ vector (approximately the velocity vector at the time of entry into the gravitational sphere of influence). **T** is arbitrary, but it is typically specified to lie in the ecliptic plane (Earth Mean Orbital Plane and Equinox of J2000.0 (EMO2000)), or in a body equatorial plane (Earth Mean Equator and Equinox of J2000.0 (EME2000)). Finally, **R** completes an orthogonal triad with **S** and **T** (i.e., $\mathbf{R} = \mathbf{S} \times \mathbf{T}$). A target point can be described in terms of the B-vector dotted into the **R** and **T** vectors ($\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$). The spacecraft state in the B-plane can be represented by the following six

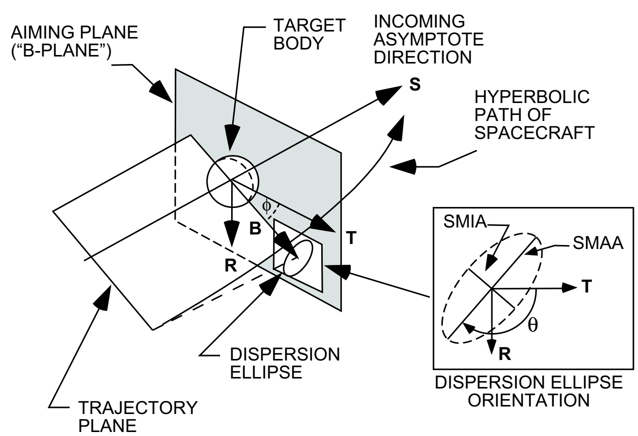


Figure 12. B-Plane Coordinate System

quantities: $\mathbf{B}\cdot\mathbf{R}$, $\mathbf{B}\cdot\mathbf{T}$, TF (time-of-flight), $\mathbf{S}\cdot\mathbf{R}$, $\mathbf{S}\cdot\mathbf{T}$, and C_3. $\mathbf{S}\cdot\mathbf{R}$ and $\mathbf{S}\cdot\mathbf{T}$ are the declination and right ascension of the incoming asymptote $\mathbf{S}$ and C_3 is the vis-viva integral (V_∞^2). The B-plane error (miss) is determined by $\Delta\mathbf{B}\cdot\mathbf{R}$, $\Delta\mathbf{B}\cdot\mathbf{T}$, and ΔTF; the asymptote error is determined by $\Delta\mathbf{S}\cdot\mathbf{R}$, $\Delta\mathbf{S}\cdot\mathbf{T}$, and ΔC_3.

Trajectory errors in the B-plane are often characterized by a 1-σ dispersion ellipse, shown in figure 12. SMAA and SMIA denote the semi-major and semi-minor axes of the ellipse; θ is the angle measured clockwise from the $\mathbf{T}$ axis. The dispersion normal to the B-plane is typically given as a 1-σ time-of-flight error, where time-of-flight specifies what the time to encounter would be from some given epoch if the magnitude of the B-vector were zero. Alternatively, this dispersion is sometimes given as a 1-σ distance error along the $\mathbf{S}$ direction, numerically equal to the time-of-flight error multiplied by the magnitude of the V_∞ vector.

Acknowledgments

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